Performance Analysis of Intelligent Relaying in UTRA TDD

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***Abstract*—This paper concerns the analysis of Intelligent Relaying (IR), a technique to extend the capabilities of an UTRA TDD system by enabling terminals to receive and re-transmit data on behalf of other mobiles. This relaying may be enabled in all mobile units, or restricted to dedicated equipment deployed by a network operator. The aims are to reduce power, by breaking down the path between mobile and basestation into a number of shorter hops and to extend coverage into regions shadowed from direct basestation coverage. The potential benefits will depend on the efficiency of the resource allocation algorithm in coping with the multiple access interference and so a simulation tool has been developed to analyse the performance of IR. Results show that IR can provide benefits in the case where basestations are sparsely deployed and also offers power reduction compared to a conventional TD/CDMA scheme under conditions of light call loading.**

I. Introduction

Intelligent Relaying (IR) is a technique in which terminals are permitted to receive and retransmit data on behalf of other users. This concept has been proposed as an enhancement to cellular networks such as UTRA TDD [1, 2] and was considered for inclusion in 3rd Generation specifications [3]. Allowing intelligent data forwarding in a cellular network offers potential improvements in coverage by permitting connections for mobiles in locations that would otherwise be shadowed for direct coverage from a basestation, or that are beyond the regular boundaries of the cell. This coverage can be achieved by offering route diversity, such that where the direct path from a particular mobile to a basestation is unavailable, communication may still be possible via a conveniently located relay node. Another important advantage of IR is that it permits lower power levels than a direct mobile-basestation connection, by allowing the possibility of choosing a relay route that comprises a number of short hops. In addition to extending coverage and battery life (and helping to allay possible health concerns), lower power levels will also lead to reduced interference, and the possibility of an increased user capacity. The operation of a cellular network using IR is depicted in Figure 1 which shows how the route between mobile and basestation can be broken down into shorter mobile-mobile hops and how IR nodes can act as forwarding nodes for a number of mobiles.

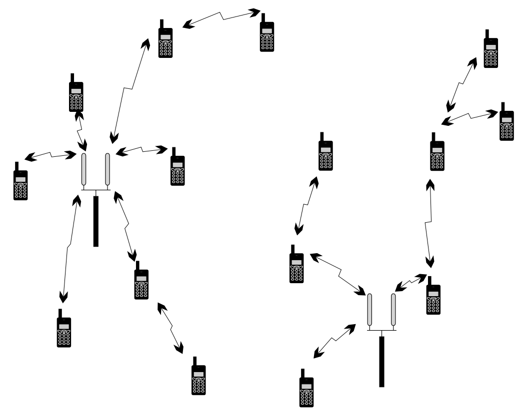

Fig. 1. Intelligent Relaying

II. Implementation of IR

A. Air interface

The air interface is chosen to be compatible with the UTRA TDD mode, this means that every individual transmit channel required as part of the chain between mobile and basestation is created by the allocation of a timeslot and spreading code. Variability of data rates is achieved by allocating codes with differing spreading factors (as described in [4]). The air interface allows potential compatibility with non-relay capable nodes (e.g. standard UMTS terminals) allowing them to take advantage of multi-hop connections formed via IR enabled nodes.

B. Route selection and resource allocation

For a typical call to be established via IR between a mobile and a basestation, the IR algorithm must select the best available relay nodes and allocate suitable resources for each individual hop of the connection. The route selection algorithm is described further in [5] and acts to ensure that the resources chosen minimise the interference caused to other nodes transmitting at the same time (in order to maximise the potential capacity). This resource allocation is handled on a central basis by the basestation within each cell, in contrast to ad hoc networking techniques where resource allocation is usually handled by each node as required.

The proposed algorithm takes account of the actual interference conditions at each node and the resources already allocated elsewhere. This means that the route established is one that is actually achievable, rather than one that offers a theoretical minimum power value. It's also desirable to minimise the end to end delay, so time adjacent timeslots are used to receive and retransmit at each intermediate node.

It may be a concern that ad hoc networks could require an excessive amount of signalling between nodes in order to establish connections efficiently. It is therefore proposed that a simple selection of operational and measured data is sent from each node in the network to the serving basestation (which is the ultimate authority for route selection and resource allocation). This requires that a data table is maintained at each basestation, comprising for each node:

1) for each timeslot in use; the power (for transmit slots), code identity and spreading factor of each code in use.
2) the level of interference measured on timeslots that are being used to receive.
3) the identities of the 10 "closest" neighbour nodes, established through monitoring of signal strength levels, supplemented by active probing.

C. Power control

Implementing multi-hop techniques in a CDMA network introduces additional difficulties for a successful power control strategy. A conventional CDMA network operates by ensuring that, wherever possible, wanted and interfering signals are received at the same power level [6] to avoid the near-far effect. This is achievable for a single cell CDMA network, as for the uplink all transmission are received at a single destination (the basestation), and for the downlink all transmissions emanate from the same source. For the IR network however, there is a multitude of transmissions occurring at different locations within the same cell, causing potential power control problems. IR allows an additional degree of freedom, in that potential interfering transmissions can be placed on different timeslots. In order to prevent excessive interference between nodes, it is necessary to review the power levels as the propagation and network loading conditions change. Thus a closed loop power control function is implemented, as specified by 3rd Generation standards [4]. Low values of interference between nodes will be critical in order to maximise the potential for capacity enhancement this must be achieved by keeping the transmit powers to as low values as possible.

D. Fixed relay nodes

In order to simplify power control, it may be preferable to restrict relaying capability to units deployed in fixed locations by a network operator. In this study, these fixed nodes are known as ACORNs (Adaptive Cellular Overlay Relay Nodes). Fixing the relay nodes in this manner has the advantage that the sources of additional interference caused by relaying will be in predictable locations, thus simplifying relay route selection and resource allocation. It also removes the requirement for users to have more complex IR-capable handsets. The fixed relay nodes use the same bandwidth allocation as conventional mobile nodes and so both types of nodes appear identical to the resource allocation mechanism making the deployment of fixed nodes straightforward. As the relay nodes are in static positions, they can be equipped with directional antennas aligned towards the appropriate basestation to allow further control of interference.

E. Call establishment

Each time a new call is initiated in the network, the distribution of interference changes, so calls that are established when the cell loading (and interference potential) is low tend to route via the maximum number of nodes (in order to keep the transmit power at a minimum). As further calls are established, these calls cause, and are susceptible to, further interference. The algorithm therefore also incorporates a mechanism to identify which of these calls should be rerouted in order to minimise the aggregate interference.

III. Simulation

The random factors involved in the network (the positions of the nodes and the random nature of propagation losses of multiple radio links) will all affect the performance results and are difficult to model mathematically. Mathematical modelling can demonstrate theoretical power savings but can't actually emulate the efficiency of the network in resource allocation, which will be critical to ensure correct operation.

A flexible computer simulation tool has been developed that implements the proposed IR algorithms and permits the analysis of various deployments of IR. Varying numbers of mobiles can be placed in a given simulation area, which can also be seeded with fixed relay units if desired. Propagation models for mobile-mobile and basestation-mobile channels have been developed based on measured environments [8], supplemented by a statistical shadowing model. This approach allows the operation of IR to be analysed in macro, micro and pico-cellular environments. The simulations are performed in the 2GHz band, and IR can be disabled in order to facilitate comparison with a conventional UMTS implementation. The actual outputs of the simulation platform comprise the number of calls that can be set-up and the power required at the relay nodes in order to support these calls.

Various scenarios can be created to test the operation of IR in different environments and with different numbers and locations of users and fixed relay points. The number and location of basestations, IR enabled relay nodes, IR disabled relay nodes and ACORNs can be specified, whilst outdoor and indoor environments can be simulated by choosing different propagation models. Target E_b/N_o and maximum/minimum permissible transmit powers can also be set.

IV. Results

Three different scenarios are chosen in order to demonstrate the performance of IR. An outdoor environment is considered by specifying the propagation models developed for mobile-mobile and mobile-basestation channels based on outdoor measurements [8]. The number of users in the network is varied; in each case, the network is loaded to its maximum capacity by attempting to establish (and re-established where necessary) as many calls as possible. For each deployment and user density, simulations of three different implementations are performed:

1) a network where IR-disabled mobile nodes are deployed randomly and evenly across the test area, ACORNs being deployed at a distance of 100m from the basestation. This implementation is referred to as *IR with ACORNS*.
2) a network which operates as a TD/CDMA network with no IR-enabled nodes nor ACORNS. This is referred to as *non-IR*.
3) a network in which all the mobile nodes are deployed randomly as described previously. All are permitted to relay, this case being referred to as *IR no ACORNS*.

In this study, IR is implemented as an optional addition to a cellular network and so all calls are ultimately routed via a basestation. It was shown in [7] that further gains are possible if calls between users in the same cell do not require routing via a basestation. Each basestation has a finite capacity and so places a limit on the number of calls that can be established per cell, this value being similar to that of the conventional CDMA network. Gains may be possible in a multicellular case due to the ability of the technique to reduce levels of inter cell interference by offering mobiles that are located on the edges of cells a reduction in transmit power.

A. Heavily loaded outdoor cellular network

The layout of the cells for the network being simulated consists of 7 basestations in a conventional hexagonal pattern in a total simulation area of 1000mx1000m, the basestation spacing r being 400m. Where ACORNS are used, 4 are placed in each cell, at a distance of 100m from the basestation (i.e. half the cell radius) and modelled as having antenna patterns which offer a 30dB reduction in path losses to the basestation. Multiple simulations of each case with independently distributed random user positions were performed, the results presented represent a mean of the values produced.

Figure 2 shows the average aggregate power required to establish a call. This power value is calculated by summing the total amount of power used for all the connections when the network has been fully loaded and then dividing by the total number of calls possible.

Figure 3 is derived in a similar manner, but only the power used by each mobile node to send its own data is considered (i.e. power used to relay is not included). Recording these values help to give an indication of how much relaying activity is taking place and can also demonstrate the benefits of IR from the point of view of the mobile terminals (as the power for transmissions from relaying nodes is not included). The number of calls that can be accommodated (i.e. the capacity) is shown for each case in Figure 4.

The average aggregate power per call (shown in Figure 2) rises to a value in the range 10-13dBm irrespective of whether IR is used and whether ACORNS are deployed. Similarly, the capacity figure is fairly constant in the range 37-40 users in the area under consideration.

There appears to be no significant variation of results with user density. When there is no IR at all, or when IR is limited to ACORNS, it would be expected that the density of users would

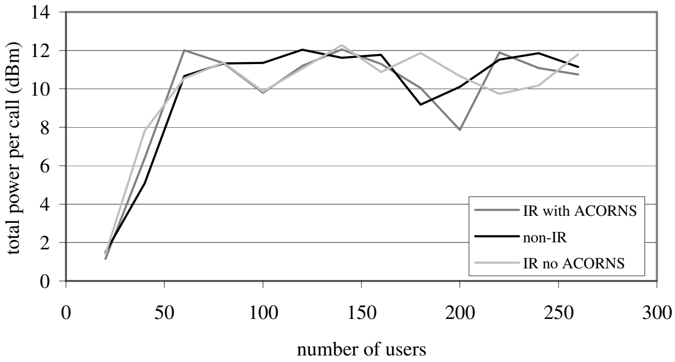

Fig. 2. Aggregate power required per call, heavily loaded network

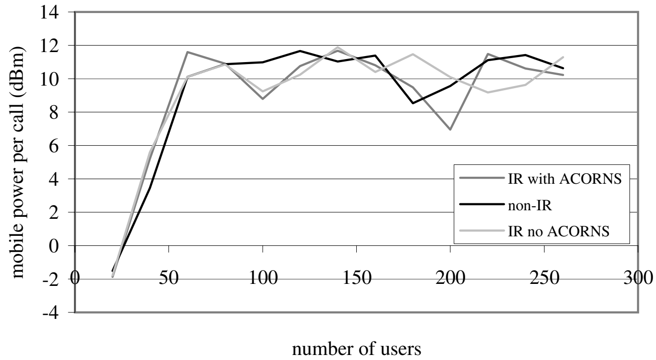

Fig. 3. Mobile power required per call, heavily loaded network

make little difference, however for the case where all the nodes are IR enabled, some improvement in performance would be expected due to the effects of route diversity.

These results suggest that the network incorporating IR isn't working as well as might be wished. It is possible to gain some insights into how the algorithm is handling calls by considering the difference between the aggregate and the mobile powers (Figures 2 and 3). The mobile power and aggregate power figures are different when the number of relay nodes is low, but tend to the same value as the number of relay nodes increases. This suggests that less relaying takes place as more nodes are added, possibly due to the greater potential for interference (recalling that the IR algorithm in use acts to reduce the global interference. The small difference between the aggregate and mobile power values (this difference being the power supported by the relays) when the user density is low suggests that the relaying is being carried out by the ACORNS, which are equipped with directional antennas and therefore only transmit a small amount of power.

In general the performance results are disappointing. In particular, the possible capacity gains compared to a conventional CDMA network due to the reduction in transmit power of the nodes in the vicinity of the cells' edges have not materialised. There seems to be no difference between the values irrespective of whether ACORNS are used. What appears to happen is that as the activity in the network increases, the number of calls established through IR drops, such that in effect, the fully loaded

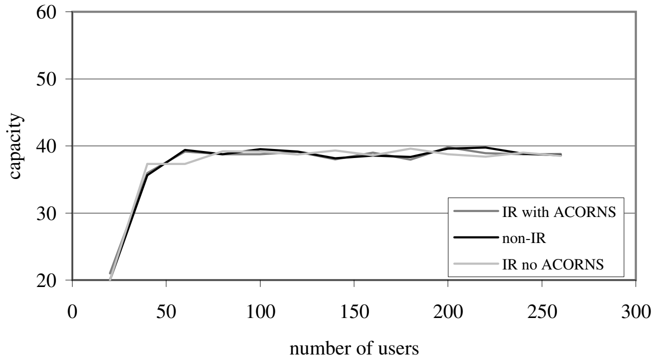

Fig. 4. Network capacity, heavily loaded network

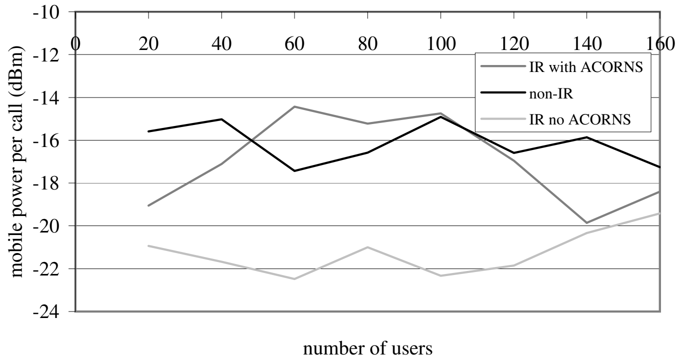

Fig. 6. Mobile power required per call, lightly loaded cell

IR cases simulated are identical to the non-IR case.

It can be concluded that for the heavily loaded outdoor cellular environment simulated, the mutual interference caused by IR transmissions still limits the capacity and power saving potential. Using CDMA for multiple transmissions within the cell creates an amount of interference that limits the capacity, even with an algorithm that can co-ordinate the resources and powers in use to minimise the mutual interference. This capacity limit holds even when the mutual interference caused by relaying is restricted in area by the use of directional antennas. The result of this is that as more calls are added, the control algorithm recognises that the interference is too high and has to reduce the number of transmissions by dropping calls that have been established over multiple hops and establishing new calls via direct mobile-basestation links. This accounts for the similarity in the mobile and aggregate powers per call and the capacity figures.

B. *Lightly loaded cellular network*

In order to test the behaviour of IR in a lightly loaded network, a test environment is established comprising a single 1000mx1000m cell with the basestation at its centre. The cell is loaded with just 5 calls.

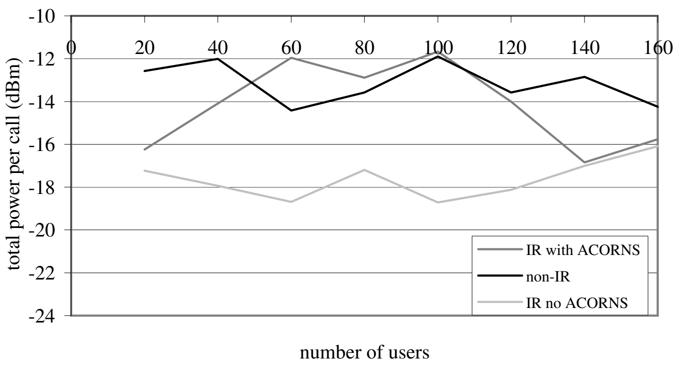

Fig. 5. Aggregate power required per call, lightly loaded cell

For this set of tests, the benefits of power reduction become apparent. Figure 5 shows a clear fall in the aggregate power required to establish a call via IR of 4-8dB compared with the case where there is no IR. It can also be deduced that there is more relaying activity going on, as the difference between the aggregate and mobile only transmit power values (in Figure 6) is significantly higher than for the fully loaded network cases.

Using ACORNs in this case seems not to be of great benefit, probably because the path losses are sufficiently small so as to permit low power whatever mechanism is used. The simulation incorporates a hard lower transmit power limit for each node of -40dBm which may be reached in the case of low path losses, particularly by an ACORN when directional antennas are used. This lower limit may prevent a further reduction in interference levels.

C. *Sparse cellular network*

In order to test the effectiveness of IR in providing coverage between cells, tests on a network that has infrastructure sparsely deployed are carried out. This is achieved by creating a 30000m^2 network with 4 cells deployed. This implies significant coverage gaps between the basestations. Were a network operator to cover a similar sized area with non-relaying techniques, it would be expected that a significantly greater number of basestations would be necessary, implying increased costs for hardware, site acquisition and planning. The IR system should allow calls to be established to mobile nodes that are located in these gaps.

As the aim is to extend coverage, rather than to reduce interference on the cells' edges, the ACORNS were placed closer to the edge of the cell boundary than for the cellular cases, the ACORN radius being 3500m. This position allows the ACORNS greater coverage into the areas not served directly from the basestation. The number of users deployed in the network was varied in the range 100-280.

As can be seen from Figure 9, using either of the IR configurations offers the possibility for an increase in users compared with the non-IR case. This comes about not as a result of greater CDMA capacity through lower inter-user interference, but rather through offering the possibility of connection via IR to users that are located outside direct coverage from a basestation.

From Figures 7 and 8, for the IR configuration with no ACORNS, there is a higher aggregate power per call than the *IR with ACORNS* case, whilst approximately the same number

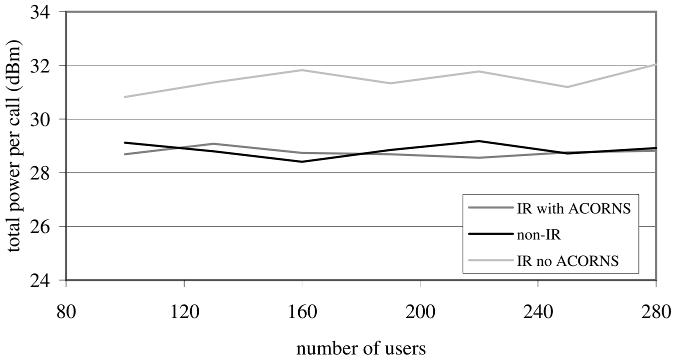

Fig. 7. Aggregate power required per call, sparse outdoor network

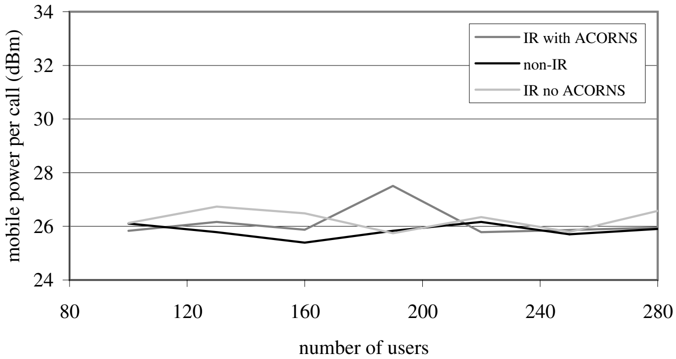

Fig. 8. Mobile power required per call, sparse outdoor network

of users are supported. The mobile power is about the same for the two cases, and so the ACORNS offer a method of lowering the transmit power.

The maximum number of users deployed was 280, which implies that the greatest user density is some 800 times smaller that the outdoor network simulated previously. However, computing limitations mean that, lamentably, this number of users is the greatest with which the simulation platform can cope. It is possible that the technique may have shown greater scope for performance enhancement if a greater user density were to be achievable.

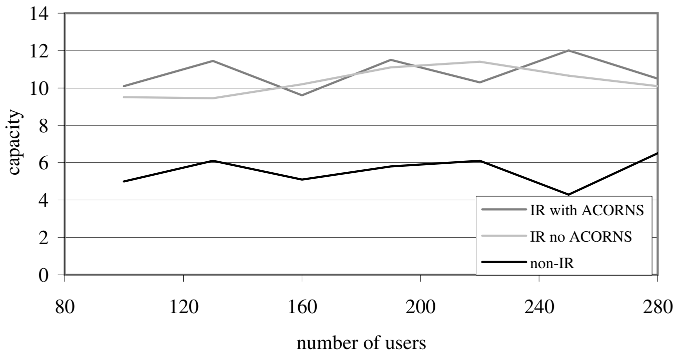

Fig. 9. Network capacity, sparse outdoor network

V. Overall conclusions

The aim of this paper has been to test the predicted performance advantages of a TD/CDMA network in realistic outdoor environments. Heavily loaded cellular systems have been simulated, as has the operation of IR under conditions of light loading. Additionally, tests have been carried out to determine the effects of using IR to provide connections to areas between the regular coverage area of cells, similar to the ODMA proposal for UMTS [3]. The use of a multi-cell system was expected to improve on the capacity offered by conventional TD/CDMA networks by reducing the amount of intercell interference. The technique, in conjunction with fixed relay units, was shown to offer reduction in transmit powers in the case of lightly loaded networks and the possibility to extend coverage in the case where there is insufficient direct coverage from the basestation.

In order to provide a straightforward upgrade path from a conventional UMTS implementation, an omni-directional antenna has been assumed at the basestation. However, additional improvements would be expected if directional antennas aligned towards the relay units were provided. This would, however, require additional capability at the basestation to provide for antenna switching according to whether communication was being carried out with a relay node (via the directional antennas) or via other mobile nodes (via the standard basestation antenna). A possible intermediate step would be to replace the main basestation omni-directional antenna with directional antennas to provide a sectored basestation, with one relay unit active per sector.

Acknowledgements

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